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Axial crushing of metal-composite hybrid tubes: experimental analysis

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Abstract

In the automotive sector, special attention is paid to the study of the behavior of the structural components that make the car bodies. The continuous demands on the weight saving imply the car bodies to be assembled with components made in different materials and using different manufacturing processes. Considering the making of the sacrificial structures aimed to the energy absorption, composite materials are increasingly used to replace conventional metal materials. However, the use of composites is accompanied with a change in the type of deformation obtained during the impact phenomenon. Usually, with the conventional metal materials, the crushing behavior is a progressive buckling whereas the composite materials are characterized by a brittle fracture. The combination of the traditional metal materials with the composite ones can represent a good solution to obtain high levels of performance.

In this context, the structural performance of metal-composite hybrid tubes subjected to quasi-static axial crushing is experimentally evaluated in this work. The specimens, with circular cross section, were obtained with tubes made in a fully thermoplastic composite internally reinforced with aluminum tubes. The composite material used were made in polypropylene both for the matrix and for the reinforcing fibers. This material has a good axial absorption capacity but irregular behavior during crushing. The addition of a conventional material as reinforcement allowed to increase the absorption capacity by ensuring a more progressive and controlled crush. The analysis was carried out by evaluating, for various geometric configurations, different parameters (mean load, average stress, specific energy, efficiency). The results, discussed in the work, showed how the energy absorption performance of a hybrid structure are higher than the sum of the performance of the single materials.

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1. Introduction

The demand to improve the crashworthiness efficiency of vehicles has been raising up in the last years in order to decrease the injuries due to the crash events, considering also the increasing speed of vehicles. Therefore, the interest to use energy absorber devices with higher energy absorption capacity has increased along the years. Circular metal tubes are one of the most common shapes of tubular devices for energy absorption. These devices, called also crash box, absorb the kinetic energy of an impact by collapsing in a progressive and controlled way. The so called concertina and diamond modes are the two main crushing behaviors that can be obtained, with this type of specimens, under quasi-static and dynamic axial loading conditions (Eyvazian et al. 2017). In the last decades, few methods were suggested to improve the energy absorption capability of these kind of structures. One of this is the expansion of metal tubes using rigid rings on the tube to activate the axisymmetric plastic buckling mode (Shakeri et al. 2007). Another interesting solutions are the use of filler substances such as metal and polymeric foams (Santosa et al. 2000, Kavi et al. 2006, Peroni et al. 2008, Avalor et al. 2014, Pandarkar et al. 2016) or to apply an external reinforcement made in composite materials (Wang et al. 1991, Hanefi et al. 1996, Song et al. 2000, Bouchet et al. 2002, Mirzaei et al. 2012, Kim et al. 2014).

Many researchers studied the axial crushing of metal tubes reinforced by composite layers, called also hybrid tubes, from the experimental (Wang et al. 1991, Kim et al. 2014, Zhu et al. 2017) and numerical (El-Hage et al. 2006, Huang et al. 2012) point of view. The results of these researches showed that various parameters could contribute in collapsing and affect the crashworthiness characteristics (absorbed and specific energy, mean and peak load, crush force efficiency). The crushing behaviors of metal/composite hybrid structures can be affected by geometry, lay-up sequence of composite, surface treatment, strain rate, etc. The idea to improve the energy absorption capability of metal tubes through composite reinforcement was introduced for the first time by Wang et al. (1991). Song et al. (2000) studied, from an experimental point of view, the effects of many factors like the strain rate, the composite wall thickness, the fiber ply orientation in pattern and the mechanical properties of metal tube subjected to impact load. They obtained four main collapse modes for hybrid tubes including: compound diamond, compound fragmentation, delamination and catastrophic failure. Watanabe et al. (1991) investigated energy absorption capacity of steel tube wrapped in fiber reinforced composites and they showed that energy absorption is positively related to composite thickness, but decreases with the reduction of fiber orientation angle. Bouchet et al. (2002) analyzed the effect of reinforcement and different surface treatments of metal tubes in order to improve the practical adhesion between the composite and the metal tube. The obtained values of the specific energy absorption suggest that the influence of surface treatments of multi-material structures was not a significant contribution, whereas the application of the reinforcement can increase the crashworthiness performance if the same crushing mode was maintained. For the thinner aluminum alloy tube, with or without the fiber reinforced plastic composites, a diamond mode was observed. On the contrary, from a concertina mode obtained with the thicker tube without reinforcement, a diamond mode is observed with the reinforced one. As the crushing mode changed, the reinforcement applied onto the aluminum tube decreased the capacities of the tested structure to absorb energy. On the other hand, the reinforcement applied onto the thinner tube increased the SEA of the tube. Bambach et al. (2009) carried out experimental tests to explore the crushing behaviors of steel square hollow sections strengthened with CFRP. They found that application of CFRP could increase the axial loading capacity providing constraints to the development of elastic buckling deflections and thus delaying local buckling. Kim et al. (2014) investigated the collapse modes and crash characteristics of an aluminum CFRP hybrid column subjected to dynamic axial load by considering the influence of fiber orientation and lay-up sequence. El-Hage et al. (2006) and Huang et al. (2012) studied the axial crushing of circular and square hybrid tubes from a numerical point of view. They showed that for $[\pm\theta]$ ply pattern, the best angle of orientation is hoop reinforcement.

On the contrary, analytical models to predict the collapse behavior of hybrid tubes under axial loading are very restricted (Hanefi et al. 1996, Wang et al. 2002, Song et al. 2000, Shin et al. 2002, Akbarshahi et al. 2011). Hanefi et al. (1996), based on Alexander's model and considering effective crushing length, presented the first analytical model to predict the mean crushing load of circular hybrid tubes that are reinforced with unidirectional fibers in

hoop direction. Wang et al. (2002) developed the previous model considering inward and outward folding pattern and using Von Mises criterion instead of Tresca's one. They studied also the $[\pm\theta]$ stacking of composite layers, using the stress and strain transformation analysis. Song et al. (2000) considered the strain rate effects for metal material and applied the Hanefi's model for the dynamic loading. Shin et al. (2002) investigated the axial collapse of square hybrid tubes from an analytical point of view. They proposed an expression for the mean crushing load. More recently, Akbarshahi et al. (2011) and Mirzaei et al. (2012) presented mathematical models to predict the mean crushing load and the fold length of square hybrid tubes with arbitrary stacking sequence.

In this context, in this work, the structural performance of the axial crushing of metal-composite hybrid tubes subjected to quasi-static loads is experimentally evaluated. The specimens, with circular cross section, are obtained with tubes made of thermoplastic composite fabric internally reinforced with aluminum tubes. The composite material used is a polypropylene both for the matrix and for the reinforcing fibers. This material has a good axial absorption capacity but a little irregular behavior during crushing (Boria et al. 2016). The addition of a conventional material as reinforcement allowed to increase the absorption capacity by ensuring a more progressive and controlled crush behavior. The analysis was carried out by evaluating, for various geometric configurations, different parameters (mean load, average stress, specific energy absorption, crush force efficiency). The results confirmed how the thermoplastic composite fabric could also be used for structural and energy absorption purposes.

Nomenclature

n	number of the considered peaks and valleys
t_c	thickness of composite wall
t_m	thickness of metal wall
t_h	thickness of hybrid tube
L	length of tube
D	outside diameter of metal tube or inner diameter of PURE tube
A	cross sectional area
ρ	density of the material
P_{av}	mean crushing load
P_{max}	maximum crushing load
$P_{peak/valley}$	punctual force value in a peak or valley of the diagram load vs displacement
P_{var}	force variation respect to mean value and oscillation
σ_{av}	average stress
E	absorbed energy
δ	total crushing
SEA	specific energy absorption
CFE	crush force efficiency

2. Experimental set-up

2.1. Materials and geometry

The reinforcement material studied in this work is a 100% polypropylene composite (PURE, patented), both in fibers and matrix, thus achieving a mono material concept that is fully recyclable. The PURE tapes are co-extruded and consist of a highly oriented, high strength and high modulus core and a specially formulated skin on both sides for welding the tapes together in a compaction process using a hot-press (Fig.1). The combination of high stiffness and low density makes PURE an interesting material for automotive applications. Moreover, PURE material gives excellent properties with respect to impact resistance showing a soft crash behavior (Boria et al. 2017). No more brittle fracture, typical of thermosetting composite material, was shown during crushing but a ductile behavior typical of metallic materials.

As regards to the geometry, symmetrical axial tubes were used to carry out the experimental work because they are easier to fabricate with the PURE thermoplastic, and they are closer to the geometry of the actual crashworthy structures made in composites. The compound tubes were made with a metal tubes in aluminum externally wrapped with the PURE composite (Fig. 2). The outer diameters of the metal tubes D were 50, 80 and 100 mm, whereas the wall thickness t_m was fixed to 2 mm. The production of the cylindrical specimens made in thermoplastic was done by Von Roll Deutschland GmbH. The wall thickness of the thermoplastic tubes t_c varied from 2 to 4 mm with a step of 1 mm. Consequently, the total thickness of the hybrid structures is $t_h = t_m + t_c$. The length of the compound tubes was 200 mm. In the Table 1, the main details of the specimen are summarized. In order to do a comparison between hybrid configuration and traditional solutions, tubes made only in aluminum and only in PURE were also tested.

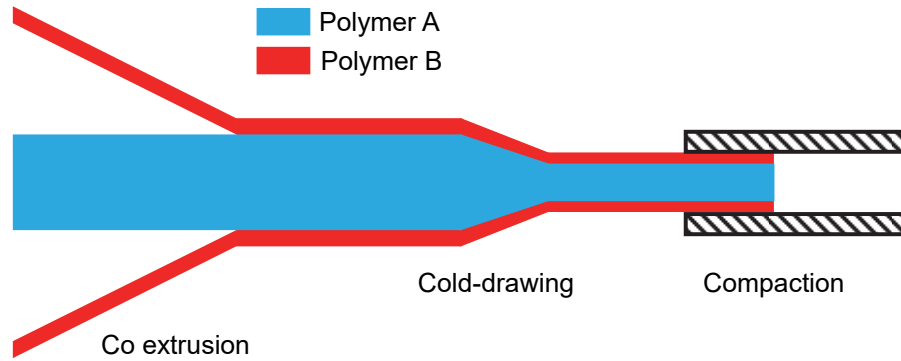


Fig. 1. Schematic processing steps of PURE.

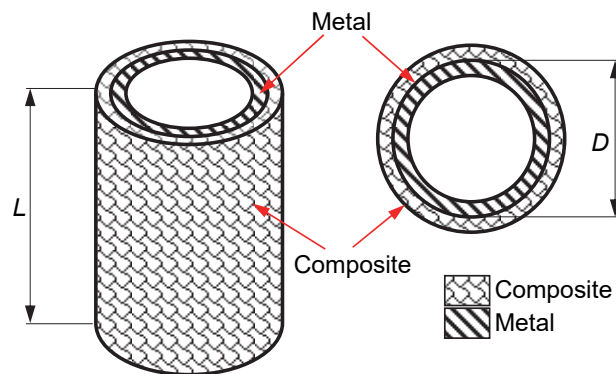


Fig. 2. Hybrid test specimen.

2.2. Quasi-static testing system set-up

The experimental tests were conducted with a 100 kN servo-hydraulic testing machine (Instron 8801). The tests were carried out at the Laboratory of the Department of Mechanical and Aerospace Engineering of the Politecnico di Torino. The specimens were submitted to quasi-static axial crushing using a speed of 5 mm/s for a maximum crushing stroke of 100 mm (Fig. 3). In some cases, the maximum force necessary to crush the structure exceeded the maximum load of the machine. Therefore, some trigger geometries were applied to these tubes as summarized in Table 1. The trigger geometries used were circular holes and 45° edge chamfering.

Table 1. Specimen details.

Specimen		Diameter	Wall thickness			Trigger	
Type	Nomenclature	D (mm)	Metal t_m (mm)	Composite t_c (mm)	Hybrid t_h (mm)	Hole	Chamfer
Aluminum	AL_50_2_(1)	50	2	0	0	-	-
	AL_80_2_(4)	80	2	0	0	X	-
	AL_100_2_(7)	100	2	0	0	X	-
PURE	PURE_50_2_(1)	50	0	2	0	-	-
	PURE_50_3_(2)	50	0	3	0	-	-
	PURE_50_4_(3)	50	0	4	0	-	-
	PURE_80_2_(4)	80	0	2	0	-	-
	PURE_80_3_(5)	80	0	3	0	-	-
	PURE_80_4_(6)	80	0	4	0	-	-
	PURE_100_2_(7)	100	0	2	0	-	-
	PURE_100_3_(8)	100	0	3	0	-	-
	PURE_100_4_(9)	100	0	4	0	-	-
HYBRID	HYBRID_50_2_(1)	50	2	2	4	-	-
	HYBRID_50_3_(2)	50	2	3	5	-	-
	HYBRID_50_4_(3)	50	2	4	6	-	-
	HYBRID_80_2_(4)	80	2	2	4	X	-
	HYBRID_80_3_(5)	80	2	3	5	X	-
	HYBRID_80_4_(6)	80	2	4	6	X	-
	HYBRID_100_2_(7)	100	2	2	4	X	X
	HYBRID_100_3_(8)	100	2	3	5	X	X
	HYBRID_100_4_(9)	100	2	4	6	X	X



Fig. 3. Hybrid specimen under quasi-static compression before (on the left) and after (on the right) the test.

3. Results and discussion

The load-displacement and the energy-displacement charts for all tested specimens are shown in Fig.4 and in Fig.5. As regards the curves of load, it is possible to note a typical first peak due to the plastic deformation for the metallic tubes. The same behavior can be also observed for the hybrid specimens whereas it is absent for the PURE tubes. In this last case, the load is much more stable, without great fluctuations and with a behavior near to an ideal absorber. Such aspect can be improved for the hybrid structures bonding together the two tubes, which were unconstrained and only in contact in this work. As it is evident in the charts of the hybrid solutions, the crushing stroke of the tubes with a diameter of 50 mm were lower than 100 mm. Those specimens were affected by side sliding and instability problems during the tests. Therefore, for these configurations, no significant results were obtained, except for the first peak load. No great variation in terms of the absorbed energy can be observed for the aluminum and hybrid tubes varying the cross section. It is evident an almost doubling value of the absorbed energy when the diameter passed from 80 to 100 mm for the PURE tubes. The same behavior was observed considering the thickness. There was a doubled value of the absorbed energy for the PURE tubes when the wall thickness was increased to 3 mm; a similar trend was also noted for the hybrid tubes.

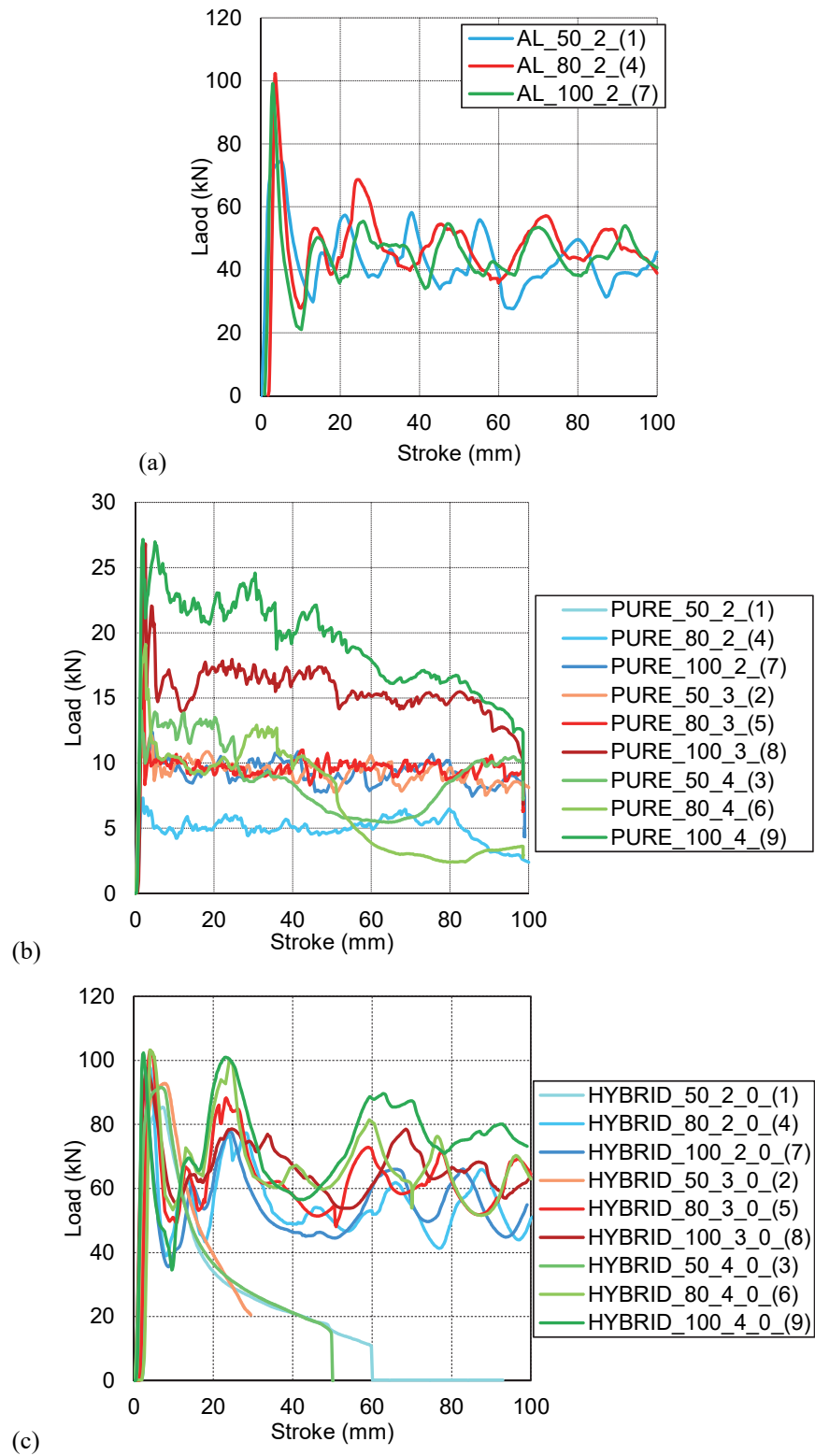


Fig. 4. Force vs. displacement for (a) bare aluminum, (b) PURE, (c) hybrid tubes.

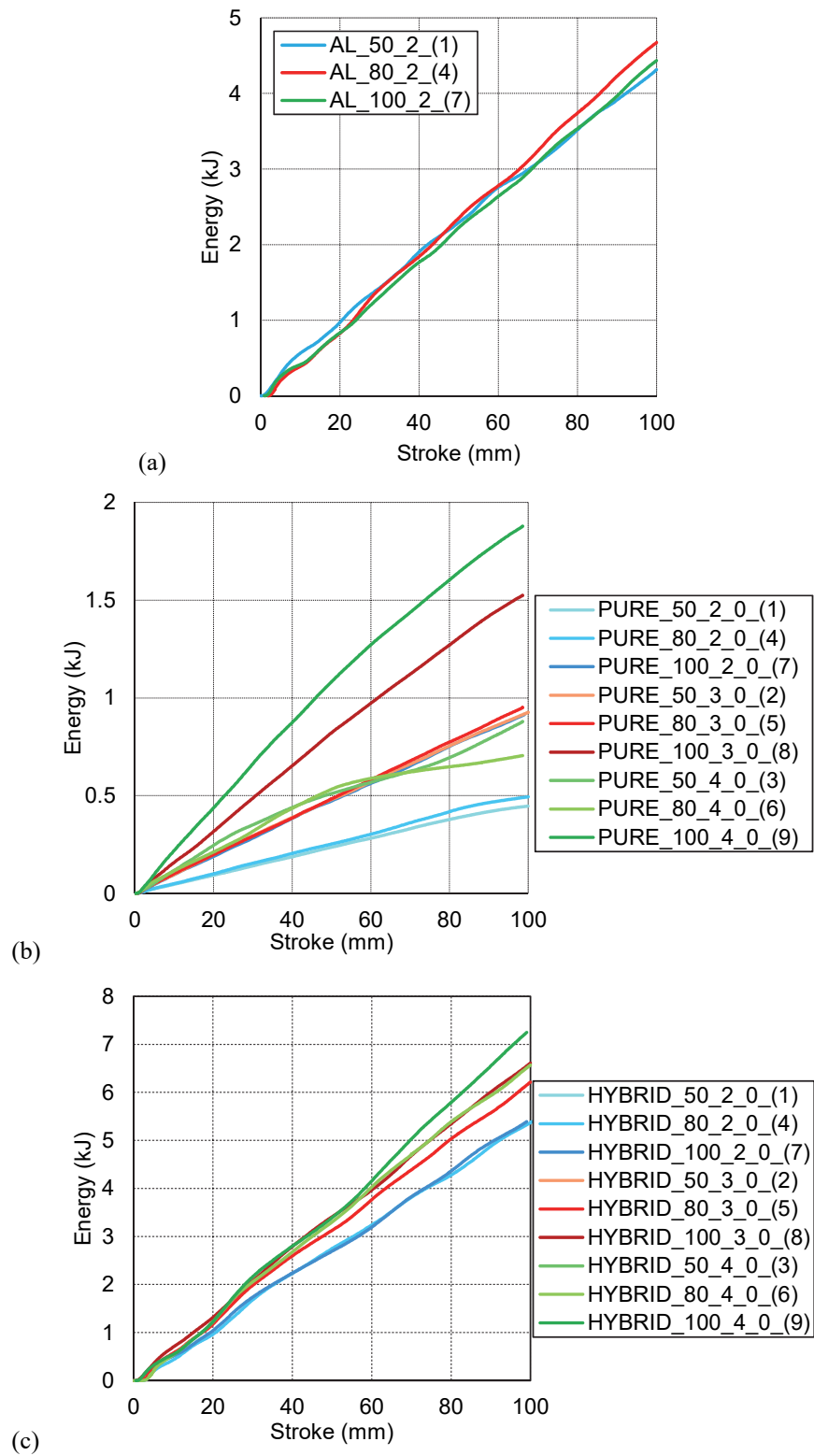


Fig. 5. Energy vs. displacement for (a) bare aluminum, (b) PURE, (c) hybrid tubes.

To evaluate the crashworthiness performance of the tested specimens, some parameters were calculated (Boria 2016, Bussadori et al. 2014). These parameters were the maximum load P_{\max} , the mean load P_{av} , the average stress σ_{av} , the specific energy absorption (SEA) and the crush force efficiency (CFE). They were defined as follows:

$$\sigma_{\text{av}} = P_{\text{av}} / A \quad (1)$$

$$SEA = E / \rho A \delta \quad (2)$$

$$CFE = P_{\text{av}} / P_{\max} \quad (3)$$

where A is the specimen cross sectional area, E is the absorbed energy, ρ is the density of the material and δ represents the total crushing displacements. The values of the crashworthiness parameters evaluated for the tested specimens are reported in Table 2. The crush force efficiency is very useful to measure the performance of an absorber. If such ratio is close to unity, the absorber is crushing at a value close to the peak load, hence minimizing the changes in the deceleration, which is dangerous for the occupant protection of a vehicle. When the crush force efficiency is equal to one, the structure is considered an ideal absorber. In this perspective, both the PURE and the hybrid tubes had higher values respect to the bare aluminum tubes.

Table 2. Experimental results of aluminum, PURE and hybrid tubes under quasi-static loading.

Specimen	P_{\max} (kN)	P_{av} (kN)	σ_{av} (MPa)	E (kJ)	SEA (kJ/kg)	CFE
AL_50_2_(1)	74.5	42.9	142.0	4.3	57.2	0.57
AL_80_2_(4)	102.3	48.6	99.3	4.7	38.1	0.47
AL_100_2_(7)	99.1	44.6	72.5	4.4	28.8	0.45
PURE_50_2_(1)	6.3	4.5	13.6	0.4	16.3	0.71
PURE_50_3_(2)	12.7	9.2	18.5	0.9	21.3	0.72
PURE_50_4_(3)	14.0	8.7	12.8	0.9	14.7	0.62
PURE_80_2_(4)	7.3	4.9	9.6	0.5	11.7	0.67
PURE_80_3_(5)	18.2	9.0	11.5	0.9	14.7	0.49
PURE_80_4_(6)	19.1	10.7	6.3	0.7	7.9	0.56
PURE_100_2_(7)	12.8	9.2	9.3	0.9	17.8	0.72
PURE_100_3_(8)	26.8	15.4	15.1	1.5	19.3	0.57
PURE_100_4_(9)	27.2	19.0	13.8	1.9	17.3	0.69
HYBRID_50_2_(1)	85.4	-	-	-	-	-
HYBRID_50_3_(2)	92.8	-	-	-	-	-
HYBRID_50_4_(3)	91.6	-	-	-	-	-
HYBRID_80_2_(4)	97.9	54.6	54.3	5.4	33.0	0.56
HYBRID_80_3_(5)	103.1	63.1	49.6	6.2	33.9	0.61
HYBRID_80_4_(6)	103.2	76.6	49.6	6.6	32.1	0.74
HYBRID_100_2_(7)	93.8	54.4	43.3	5.4	26.7	0.58
HYBRID_100_3_(8)	97.4	66.4	41.8	6.6	28.8	0.68
HYBRID_100_4_(9)	102.3	73.5	38.2	7.2	28.6	0.72

The PURE composite confirmed a soft crush behavior under axial loading. It neither splintered itself nor produced debris, but failed in a more ductile manner. All the tested tubes, both the bare and hybrid ones, absorbed the crushing energy through a plastic buckling failure mode. This was due to the nature of the thermoplastic polymers, which is different from the thermosetting ones. Indeed, in the thermoplastic polymers, the general structure is a flexible linear chain, whereas for the thermosetting ones it is a rigid three dimensional chain. It is evident how the general behavior tends to improve respect to the only PURE tube examining in detail the deformation during the crush tests for the tube with a diameter of 100 mm (Fig. 6). The tubes with only PURE material (Fig. 7) deformed with a non-regular folding, whereas the crush of the hybrid tubes followed the typical diamond buckling of aluminum structures.

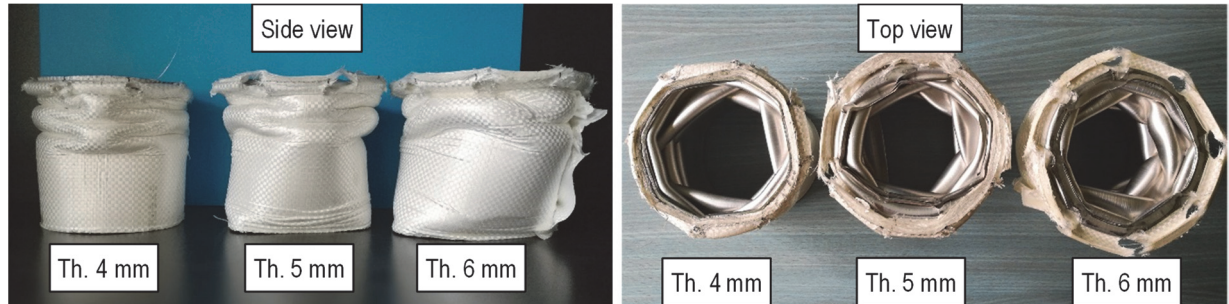


Fig. 6. Hybrid tubes with the diameter of 100 mm at the end of the crush test. From left to right the wall thickness increases. On the left a side view, on the right a top view.



Fig. 7. Side view of the PURE tubes with the diameter of 100 mm at the end of the crush test. From left to right the wall thickness increases.

Fig. 8 shows how the average crushing stress and the specific energy absorption varied as a function of the ratio between the total thickness and the outer diameter (t/D) for the PURE and hybrid tubes. Even if the data were quite scattered, in particular for the hybrid tubes, it is clear that increasing the wall thickness or decreasing the inside diameter both the values increased almost linearly. The growth is much more accentuated using the hybrid solutions, in particular considering the SEA values. This trend was also observed for thin-walled CFRP composite structures under axial loading (Boria et al. 2015).

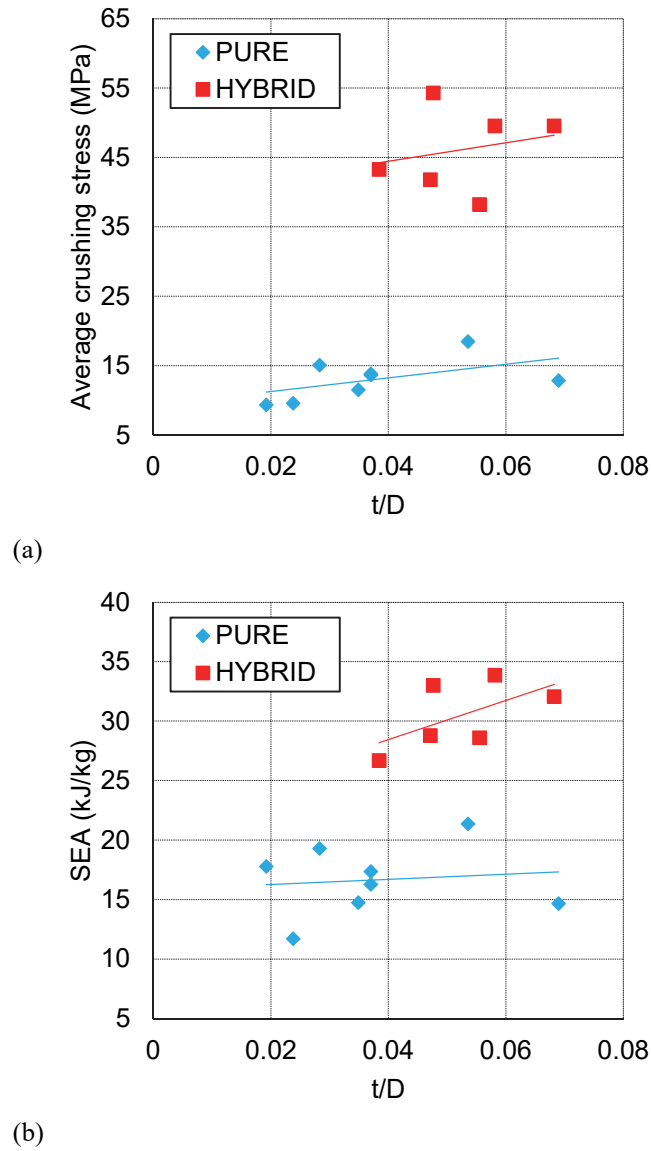


Fig. 8. Average crushing stress (a) and SEA (b) as a function of the ratio t/D for the PURE and hybrid tubes.

A linear equation can be also used to interpolate the average load as a function of the ratio t/D (defined as before), as shown in Fig 9. Comparing the results, the slope of the linear interpolation for the hybrid tubes was higher than that for the PURE specimens. Moreover, such difference was always greater than the sum of the average loads obtained with the bare aluminum tubes and that with the only PURE ones.

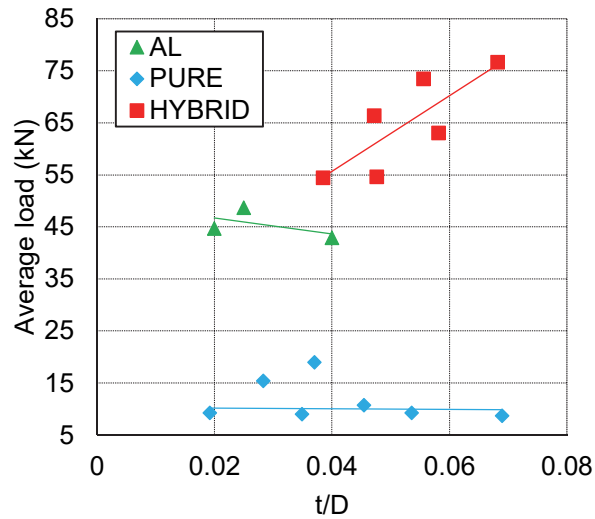
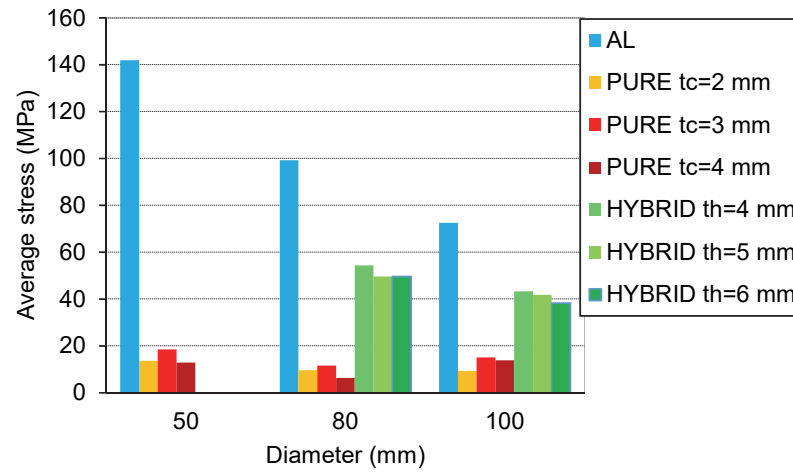
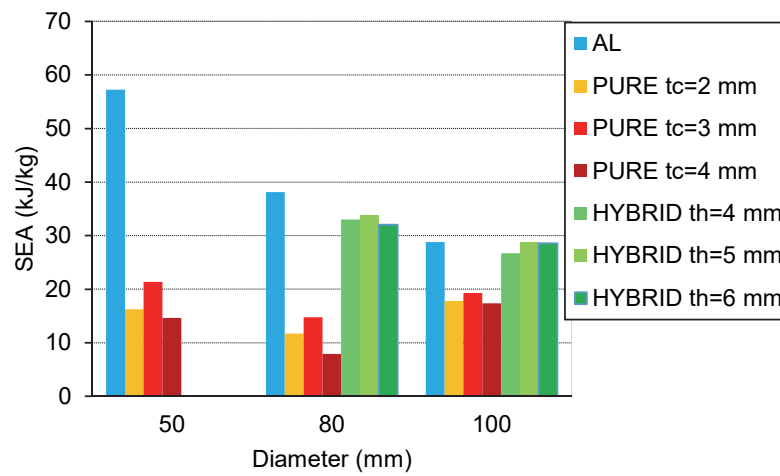


Fig. 9. Average load as a function of the t/D ratio for the tested tubes.

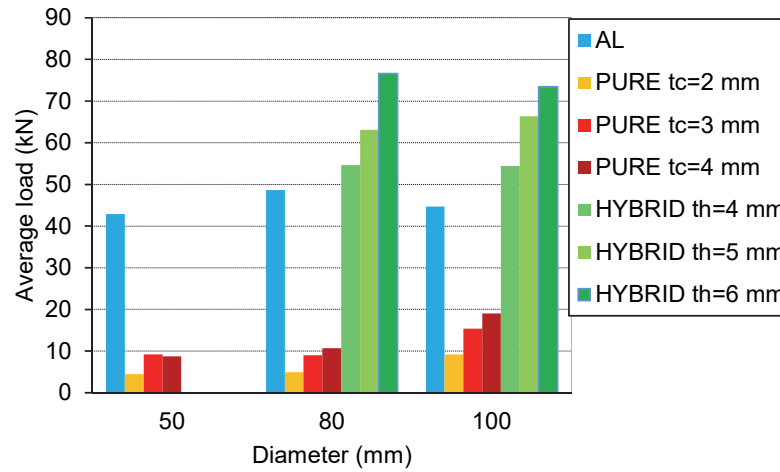
Fig. 10 shows the average stress, the SEA and the average load as a function of the value of the diameter for all the tested tubes. Considering the specific energy absorption, the highest values were obtained with the bare aluminum tubes even if the difference with the other types of tubes decreased increasing the diameter of the tube. The average stress was also greater for the bare aluminum than for the other solutions. This was due to the wall thickness that was the lowest (2 mm) for the aluminum tubes.



(a)



(b)



(c)

Fig. 10. Average stress (a), SEA (b) and average load (c) as a function of the diameter for all the tested tubes.

In Fig. 11, the stiffness of the tubes is plotted as a function of the cross section area of the tubes. The stiffness was evaluated as the slope of the load-displacement curves in the first linear section. Analyzing such values for all cases, it is evident how the fully thermoplastic tubes were less sensitive to the geometric configuration respect to the bare aluminum tubes and the addition of an external reinforcement tends to reduce such stiffness increasing the cross section. Such aspect is coherent with structures design where increasing the sizes of cross section of members can effectively increase the structural stiffness (Tianjian 2003), even if the growth rate is different depending on the material used.

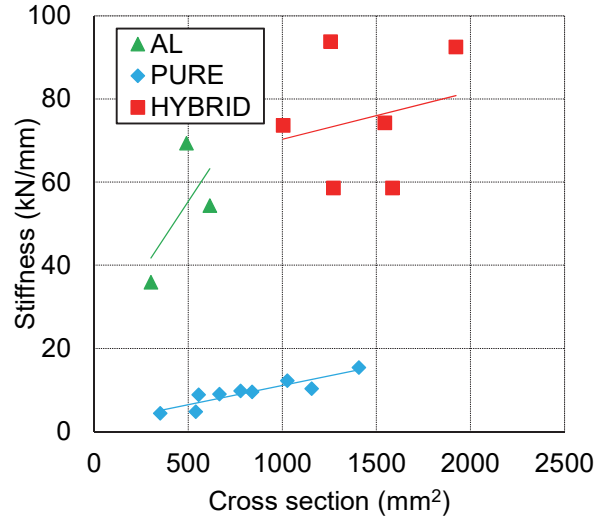


Fig. 11. Stiffness as a function of the cross section of the tubes for all the tested tubes.

Considering the load-displacement curves (Fig. 4) the PURE specimens showed quite flat behaviors whereas the hybrid tubes showed higher oscillations with periodic peaks and valleys. This trend is typical of metallic structures under axial loading. In order to analyze such variations respect to the mean load a parameter was defined as follow:

$$P_{\text{var}} = \frac{\sum |P_{\text{peak/valley}} - P_{\text{av}}|}{n} \quad (4)$$

where P_{var} is the force variation respect to the mean value, $P_{\text{peak/valley}}$ is the punctual force value in a peak or a valley of the load displacement chart and n is the number of the considered peaks and valleys. When the P_{var} parameter is zero, the structure can be considered an ideal absorber.

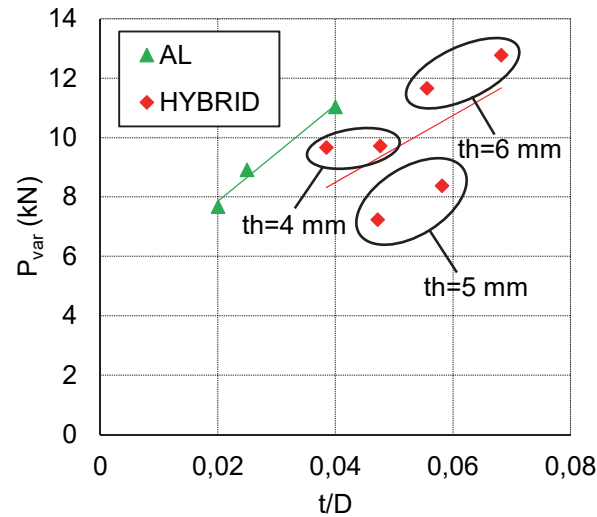


Fig. 12. Parameter of load variation for aluminum and hybrid tubes as a function of the t/D ratio.

From Fig. 12, it is evident how, in order to reduce the P_{var} parameter, the thickness of the tube should be minimized or the diameter should be maximized. This trend was confirmed for both the bare aluminum and reinforced tubes. As shown in Fig. 13, the hybrid tubes with a total thickness of 5 mm thick presented better results. Consequently, the correlation between such parameter and the geometrical data was not linear. In order to minimize the load fluctuations, and thus obtaining better crashworthiness performance, specific combinations of thickness and diameter should be adopted.

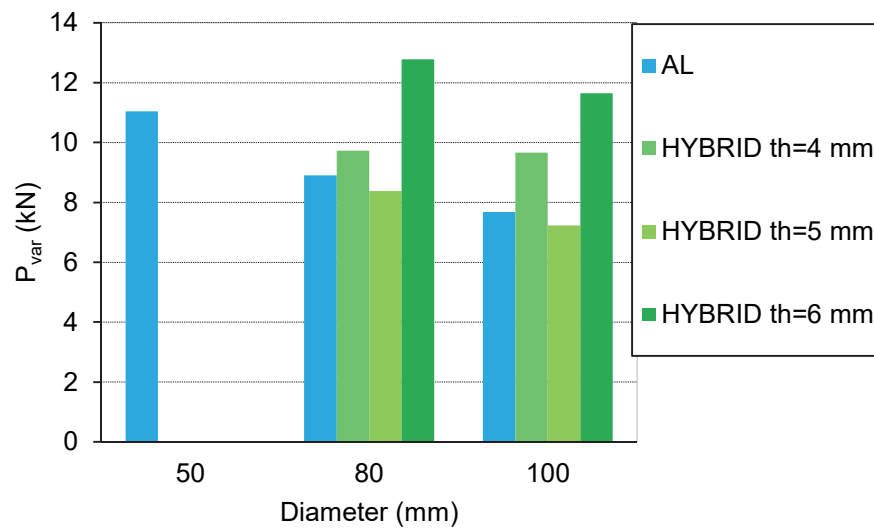


Fig. 13. Parameter of load variation as a function of the diameter of the tube.

4. Conclusions

The axial crushing of circular hybrid tubes was investigated, from an experimental point of view in this study. The hybrid specimens were made with an inner tube made in aluminum and an external one made in PURE thermoplastic. The experimental results of the crushing tests on the hybrid tubes were compared to the results of the same tests made on tube in bare aluminum and in PURE thermoplastic. The experimental results showed that the hybrid tubes had more energy absorption capability in comparison with the bare aluminum tubes when the same cross section was considered. Moreover, the experimental data indicated that increasing the thickness of the composite part, the average stress, the SEA and the average load increase with a very quick trend. Considering the average load of the hybrid tubes, such growth was always greater than the growth due to the sum of the load obtained with the bare aluminum tube and that with the only PURE one. Different crashworthiness parameters were analyzed in this work. The hybrid structures showed value of SEA not too far from the ones obtained with the bare aluminum tubes. Moreover, the use of hybrid tubes allowed to minimize the fluctuation of the crushing load during the crushing thus cutting down the decelerations applied to the structure. As future development, the behavior of the hybrid tubes could be improved bonding together the two different materials, which in this work were only in contact. This action could further reduce the fluctuations of the load typical of the metallic tubes further increasing the crush force efficiency.

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